CHARACTERISATION OF THE JOINT PROPERTIES BY MEANS OF THE COMPONENT METHOD

J.P. Jaspart
Department MSM, University of Liège, B-4000 Liège, Belgium

M. Steenhuis
TNO Building and Construction Research, NL-2600 AA Delft, The Netherlands

D. Anderson
Department of Engineering, University of Warwick, UK-CV4 7AL Coventry, UK

ABSTRACT: The present paper is aimed at describing the component method as a general tool for the characterisation of the mechanical properties of structural joints. The principles of its application in a sophisticated design approach are then pointed out. Lastly the background of the component method as it is applied in Eurocode 3 Revised Annex J is given.

1 INTRODUCTION TO THE COMPONENT METHOD

The component method may be presented as the application of the well-known finite element method to the calculation of structural joints.
In the usual characterization procedures, a joint is generally considered as a whole and is studied accordingly; the originality of the component method is to consider any joint as a set of "individual basic components". In the particular case of Figure 1 (joint with an extended end-plate connection subject to bending), the relevant components are the following :

- compression zone :
  - column web in compression;
  - beam flange and web in compression;
- tension zone :
  - column web in tension;
  - column flange in bending;
  - bolts in tension;
  - end-plate in bending;
  - beam web in tension;
- in shear zone :
  - column web panel in shear.

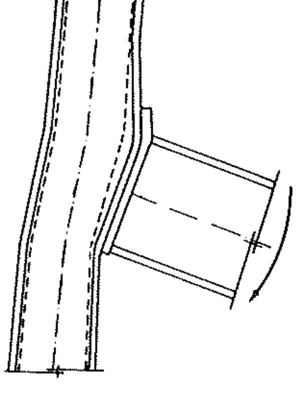


Figure 1 End-plated joint in bending

Each of these basic components possesses its own level of strength and stiffness in tension, compression or shear. The coexistence of several components within the same joint element – for instance, the column web which is simultaneously subjected to compression (or tension) and shear – can obviously lead to stress interactions that are likely to decrease the strength of each individual basic component; this interaction affects the shape of the deformability curve of the related components but does not call the principles of the component method in question again.

The application of the component method requires the following steps (Figure 2):

a) listing of the active components within the studied joint;
b) evaluation of the stiffness and/or strength characteristics of each individual basic component (specific characteristics – initial stiffness, design strength, ... - or the whole deformability curve);
c) "assembly" of the components in view of the evaluation of the stiffness and/or strength characteristics of the whole joint (specific characteristics – initial stiffness, design resistance, ... - or the whole deformability curve).

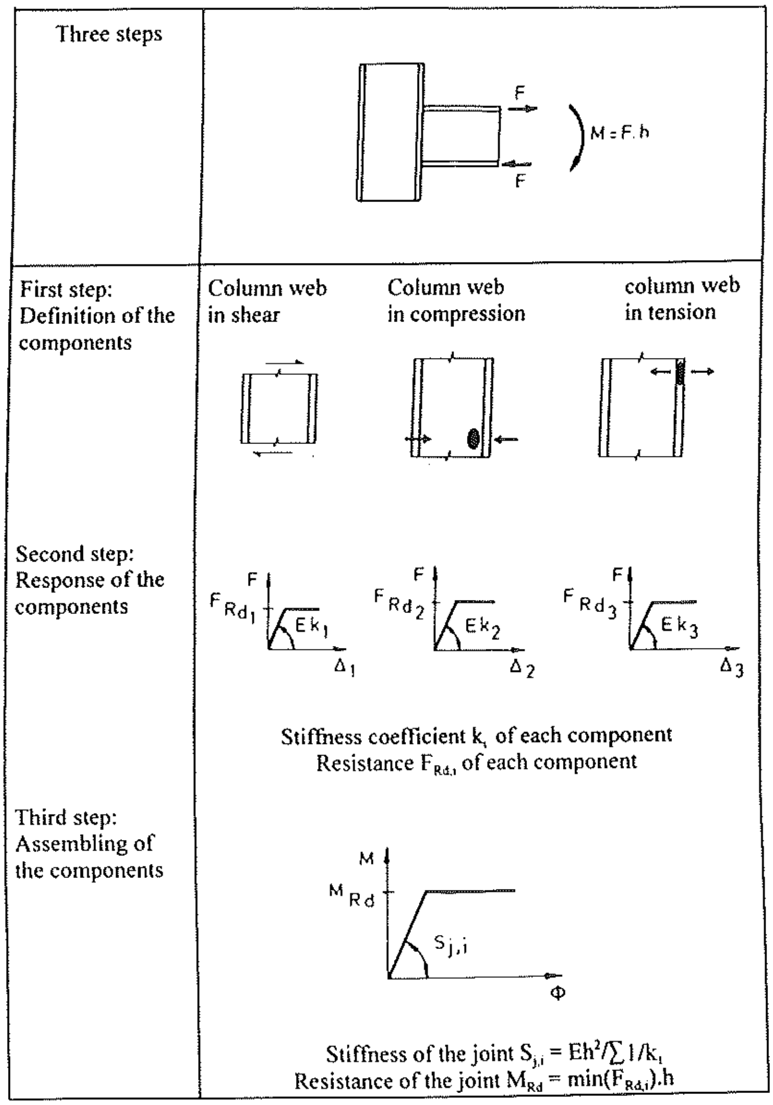


Figure 2 Application of the component method to a welded joint

As specified here above, the parallelism with the finite element method is obvious. To "component" and "joint" may be substituted the words "finite element" and "structure".

The assembly is based on a distribution of the internal forces within the joint. In reality, the external loads applied to the joint distribute, at each loading step, between the individual components according to the instantaneous stiffness and resistance of each component (see Section 2). Distributions of internal forces may however be obtained in a simpler way as discussed in Section 3.

The application of the component method requires a sufficient knowledge of the behaviour of the basic components. Those useful for usual steel joints are covered by the Revised Annex J of Eurocode 3 [1]. The combinations of the Revised Annex J components allow to cover a wide range of joint configurations, what should largely be sufficient to satisfy the needs of practitioners as far as major-axis steel beam-to-column joints and beam splices are concerned.

In the three papers following the present one in the Conference Proceedings, extensions of the set of available components are presented; they allow to widen the scope of the component method to further steel joint configurations [2], to composite joints [3] and to column bases [4].

The framework of the component method is sufficiently general to allow the use of various techniques of component characterization and joint assembly.

In particular, the stiffness and strength characteristics of the components may result from experimentations in laboratory, numerical simulations by means of finite element programs or analytical models based on theory or curve fitting. In the COST program, experimentations and numerical simulations have mainly been performed and used as references when developing and validating analytical models. These ones may be developed with different levels of sophistication according to the persons to whom they are devoted :

- Expressions covering the influence of all the parameters which affect significantly the component behaviour (strain hardening, bolt head and nut dimensions, bolt prestressing, ...) from the beginning of the loading to collapse; they fit therefore well with scientific publications;
- Simplified design procedures as in [5] constitute an ultimate step in the simplification process; the procedures for stiffness and strength evaluation are reduced to the essentials and allow a quick and nevertheless accurate prediction of the main joint properties.

Similar levels of sophistication exist also for what regards the joint assembly.

2 SOPHISTICATED MODEL FOR JOINT CHARACTERIZATION

To find how a joint behaves, the components must first be assembled to represent the configuration of the joint. An example is shown in Figure 3. The components are modelled physically as translational springs. Their response is expressed in the form of non-linear force-deformation curves. A general model will include components which take into account all sources of strength, stiffness and deformation capacity within the joint.

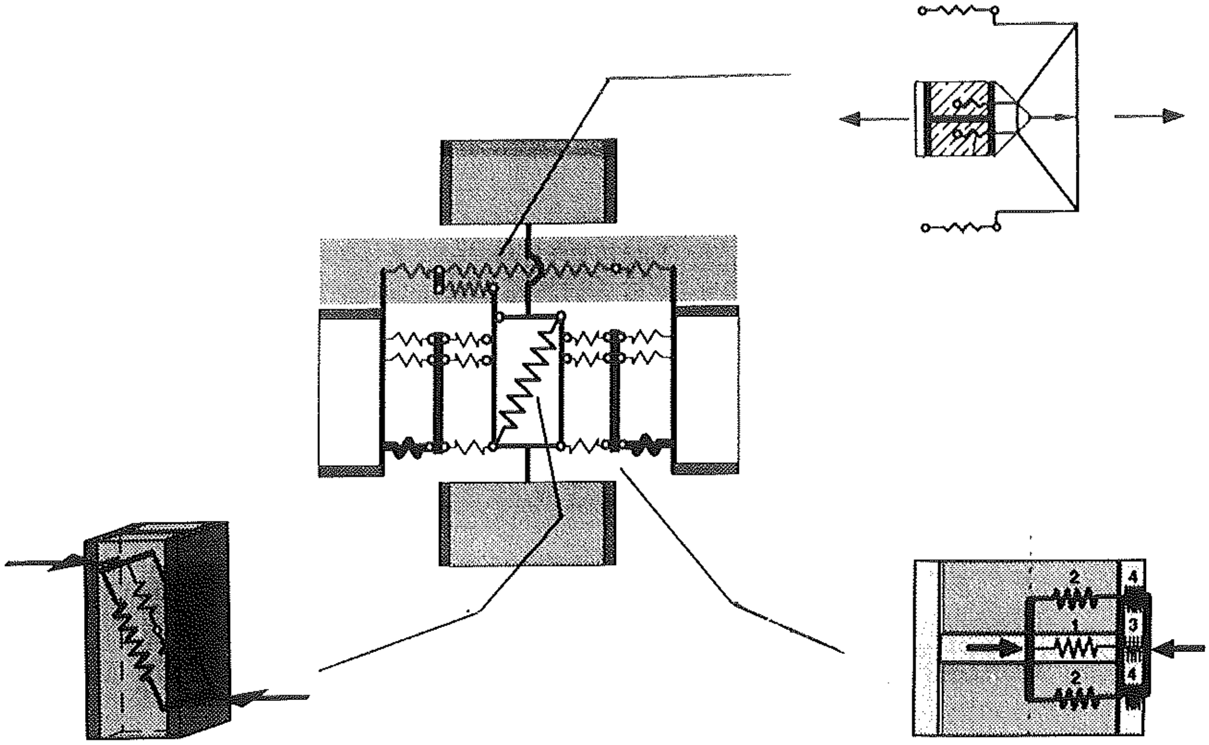


Figure 3 Sophisticated model for a composite joint

The assembly results in compatibility of displacements between the constitutive components. After assembly, a set of forces in equilibrium can be applied to the beam and column extremities to find how the joint configuration behaves. To determine the response under increasing load, incremental loading may be applied. The forces within the joint distribute between the components according to the tangent stiffness of the latter. The analysis remains valid provided that the deformation capacities of the components are not exceeded.

This way of evaluating the response of the configuration requires the use of computer software to formulate and solve repeatedly the equations characterising this iterative procedure [6]. Such software is suitable for research purposes.

The detailed configuration of a model for a composite joint is given in Figure 3 [6, 7]. To reflect the behaviour observed in tests, separate components are used to represent the connecting elements (for example, bolts and a steel end-plate) and the effect of the introduction of load into the column web. These two influences are separated by a stiff bar which ensures that the centreline of the column front remains plane, as observed in the authors' tests. This arrangement also enables an interplay between tension and compression components within the column web panel.

It can be seen from Figure 3 that groups of springs may act in parallel or in series. When subject to a specific force, a group may be combined into a single spring so as to reduce the complexity of the model. In the case of parallel components (for example a steel column web with concrete encasement), the resistance and stiffness are determined by adding the properties of the components, but the deformation capacity is that of the least ductile component. For components in series (for example an end-plate and bolts in tension), the resistance is that of the weakest component and the stiffness may be determined by a reciprocal relationship; the deformation capacity is the sum of the capacity of the weakest component and the corresponding deformation of the other components at the same load level.

For practical applications, simpler models may be used, which do not require iterative computer-based solution. These are suitable for inclusion in design codes.

3 SIMPLIFIED MODEL FOR JOINT CHARACTERIZATION

3.1 Joint deformability curve according to Annex J of Eurocode 3

The full non-linear M-ϕ curve of the Revised Annex J [1] consists of 3 parts, see Figure 4. Up to a level of 2/3 of the design moment resistance ($M_{j,Rd}$), the curve is assumed to be linear elastic. The corresponding stiffness is the so-called initial stiffness $S_{j,ini}$. Between $2/3 \cdot M_{j,Rd}$ and $M_{j,Rd}$, the curve is non-linear. After the moment in the joint reaches $M_{j,Rd}$, a yield plateau could appear. The end of this M-ϕ curve indicates the rotational capacity (ϕ_{Cd}) of the joint.

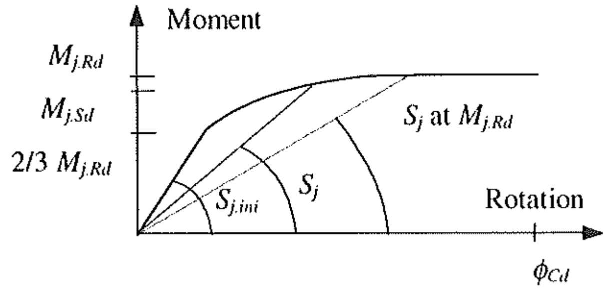


Figure 4 Non-linear M-ϕ curve in Annex J

The model assumes a fixed ratio between the initial stiffness $S_{j,ini}$ and the secant stiffness at the intersection between the non-linear part and the yield plateau (S_j at level $M_{j,Rd}$). For end plated and welded joints, this ratio is taken equal to 3, for flange cleated joints equal to 3,5, see Figure 4.

The shape of the non-linear part for $M_{j,Sd}$ between $2/3 \cdot M_{j,Rd}$ and $M_{j,Rd}$ can be found with the following interpolation formula:

$$S_j = \frac{S_{j.ini}}{\left(\dfrac{1{,}5 \;\; M_{j.Sd}}{M_{j.Rd}} \right)^{\psi}} \tag{1}$$

where ψ = 2,7 for end plated and welded joints and
3,1 for flange cleated joints.

In this interpolation formula, the value of S_j is dependent on $M_{j,Sd}$.
For practical applications, the non-linear shape of the M-ϕ curve may be idealized into a linear, bi-linear or tri-linear representation.

3.2 Annex J resistance model

In Eurocode 3 Revised Annex J, the distribution of internal forces at ultimate design state respects the three following basic criteria :

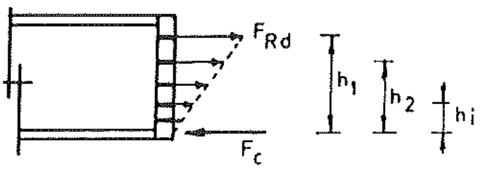
- the internal forces are in equilibrium with the forces applied to the joint;
- the design resistance of each basic individual component is never exceeded;
- the deformation capacity of each basic individual component is never exceeded.

These three criteria are sufficient to ensure the safe character of the joint design resistance evaluated on the basis of this distribution of internal forces.

Three main types of distributions may be identified in Eurocode 3 Revised Annex J according to the deformation capacity of the constitutive joint components :

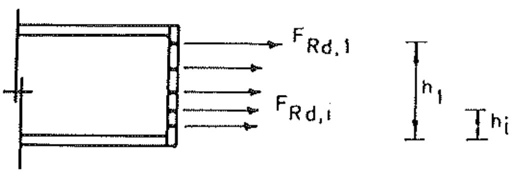
- an elastic distribution one;
- a plastic distribution;
- an elasto-plastic distribution.

They are illustrated in Figure 5 in the case of a beam splice subjected to bending moments; the figure provides also the reader with the corresponding design joint resistances.



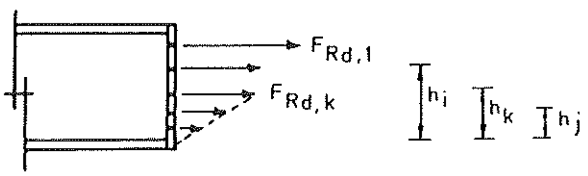
$$M_{j,Rd} = \frac{F_{Rd}}{h_1} \sum h_i^2$$

a) Elastic distribution



$$M_{j,Rd} = \sum_i F_{Rd,i} h_i$$

b) Plastic distribution



$$M_{j,Rd} = \sum_{i=1,k} F_{Rd,i} + \frac{F_{Rd,k}}{h_k} \sum_{j=k+1,n} h_j^2$$

c) Elasto-plastic distribution

Figure 5 Three types of distribution of internal forces

In the elastic distribution (Figure 5.a), the forces in the bolt-rows are proportional to the distance to the centre of compression, i.e. the centre of the lower beam flange. This distribution applies to joints with rather stiff end plates and column flanges in beam-to-column joints. The stiff character of these plates result from their thickness or from their stiffening). In Figure 5, F_{Rd} is equal to the design resistance of the first upper bolt-row in tension.

In Figure 5.b, a plastic redistribution of the internal forces takes place progressively from the upper bolt-row towards the lower ones because of their sufficient deformation capacity.

Eurocode 3 considers that a bolt-row possesses a sufficient deformation capacity to allow a plastic redistribution of internal force to take place when :

- $F_{rd,i}$ is associated to the failure of the beam web in tension or;
- $F_{Rd,i}$ is associated to the failure of the bolt-plate assembly (including failure of the bolts alone or of the plate alone) and :

$$F_{Rd,i} \leq 1{,}9 B_{t.Rd}$$

The background of the "$1{,}9\ B_{t.Rd}$" criterion is given in [8].

In some cases (Figure 5.c), the plastic redistribution of forces is interrupted because of the lack of deformation capacity in the last bolt-row which has reached its design resistance ($F_{Rd,k} > 1{,}9B_{t.Rd}$ and linked to the failure of the bolts or of the bolt-plate assembly).

In the bolt-rows located lower than bolt-row k, the forces are then linearly distributed according to their distance to the point of compression.

The three described distributions may be interrupted because the compression force F identifies itself to the design resistance of the beam flange and web in compression. The moment resistance M_{Rd} then is evaluated with similar formulae than these given in Figure in which, obviously, only a limited number of bolt-rows are taken into consideration. These bolts rows are such that :

$$\sum_{\ell=1,n} F_\ell = F_{c.Rd}$$

where :

m is the number of the last bolt-row transferring a tensile force;

F_ℓ is the tensile force in bolt-row number ℓ ;

$F_{c.Rd}$ is the design resistance of the beam flange and web in compression.

The same principles of redistribution applies to steel beam-to-column joints and composite joints subjected to bending.

3.3 Initial stiffness $S_{j,ini}$ according to Annex J

The initial stiffness $S_{j,ini}$ is derived from the elastic stiffnesses of the joint components. The elastic behaviour of each component is represented by a spring. The force-deformation relationship of this spring is given by:

$$F_i = k_i \cdot E \cdot \Delta_i \qquad (2)$$

where F_i = the force in the spring i,

k_i = the stiffness coefficient of the component i,

E = the Young modulus and

Δ_i = the spring deformation i.

The spring components in a joint are combined into a spring model. Figure 6 shows for example the spring model for an unstiffened welded beam-to-column joint.

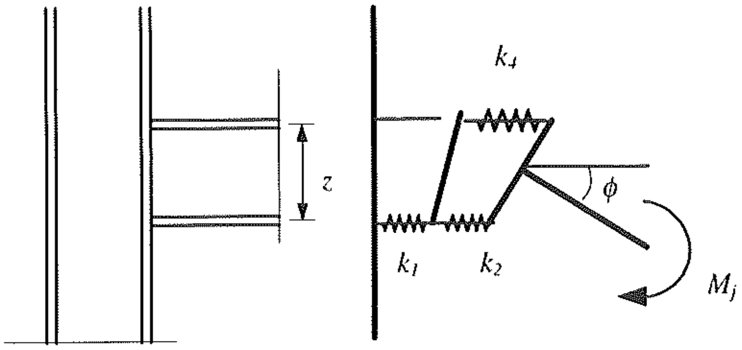


Figure 6 Spring model for an unstiffened welded joint.

In the spring model of Figure 6, k_1 represents the column web panel in shear, k_2 the column web panel in compression and k_4 the column web panel in tension. It is assumed that the deformations of the components beam flange and web in compression, beam web in tension and plate in tension or compression are included in the deformations of the beam in bending. Consequently they are not assumed to contribute to the flexibility of the joint.

The force in each spring is equal to F. The moment M_j acting in the spring model is equal to $F \cdot z$, where z is distance between the centre of tension (for welded joints located in the centre of the upper beam flange) and the centre of compression (for welded joints located in the centre of the lower beam flange). The rotation ϕ_j in the joint is equal to $(\Delta_1 + \Delta_2 + \Delta_4) / z$. In other words:

$$S_{j,ini} = \frac{M_j}{\phi_j} = \frac{Fz}{\frac{\Sigma \Delta_i}{z}} = \frac{F z^2}{\frac{F}{E} \Sigma \frac{1}{k_i}} = \frac{E z^2}{\Sigma \frac{1}{k_i}} \tag{3}$$

For an end plated joint with only one bolt row in tension and for a flange cleated joint the same formula yields. However, components to be taken into account are different.

Figure 7.a shows the spring model adopted for end plated joints with two or more bolt rows in tension. It is assumed that the bolt row deformations for all rows are proportional to the distance to the point of compression, but that the elastic forces in each row are dependent on the stiffness of the components. Figure 7.b shows how the deformations per bolt row of the end plate in bending, the bolts in tension, the column flange in bending and the column web in tension are added to an effective spring per bolt row, with an effective stiffness coefficient $k_{eff,r}$ (r is the index of the row number). In figure 7.c is indicated how these effective springs per bolt row are replaced by an equivalent spring acting at a lever arm z. The stiffness coefficient of this effective spring is k_{eq}. The effective stiffness coefficient k_{eq} can directly be applied in formula 3. The formulae to determine $k_{eff,r}$(4), z (5) and k_{eq} (6) can directly be derived from the sketches of Figure 7. The bases for these formulae is that the moment-rotation behaviour of each of the systems in Figures 7.a, 7.b and 7.c is equal. An additional condition is that the compressive force in the lower rigid bar is equal in each of these systems, in other words:

$$k_{eff.r} = \frac{1}{\sum_i \frac{1}{k_{i.r}}} \qquad (4)$$

$$z = \frac{\sum_r k_{eff.r} \cdot h_r^2}{\sum_r k_{eff.r} \cdot h_r} \qquad (5)$$

$$k_{eq} = \frac{\sum_r k_{eff.r} \cdot h_r}{z} \qquad (6)$$

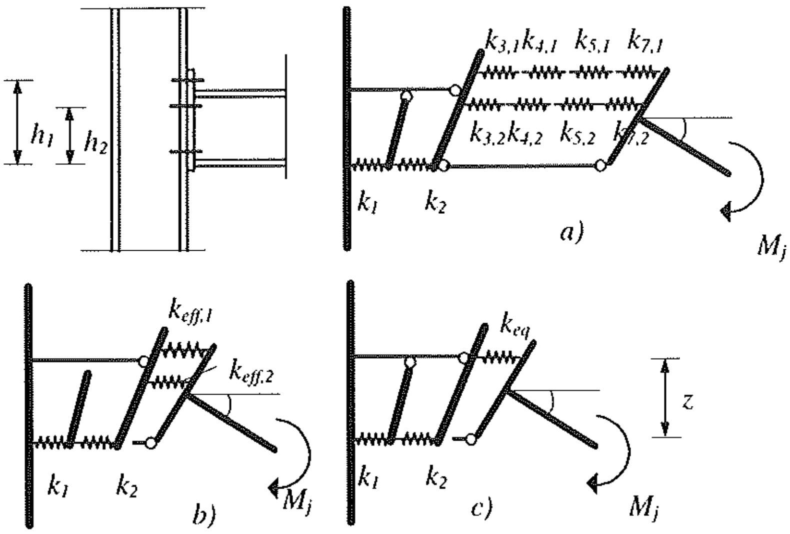


Figure 7 Spring model for a beam-to-column end plated joint with two bolt rows in tension.

3.4 Annex J ductility model

It is not usual for designers to calculate either the required or available rotation capacity of structural elements. Rotation capacity is essential though if redistribution of bending moments is assumed in global analysis. For members, well-known classification systems are used to ensure that adequate rotation capacity is available [11]. With semi-continuous construction, rotation capacity may be required from the joints rather than the members. As a result, Annex J of Eurocode 3 gives guidance on joint ductility.

Component models can be used to calculate the rotation capacity of a joint, provided that the limiting deformation capacity of each active component is known. For steel joints though it is often sufficient to rely on the observed behaviour of critical joint components. Thus for bolted joints the revised Annex J permits the designer to assume sufficient rotation capacity for plastic global analysis provided that the moment resistance of the joint is governed by the resistance of one of the following:

- the column web panel in shear
- the column flange in bending
- the beam end-plate in bending
- the tension flange cleat in bending.

For composite joints (Figure 3), yielding of the slab reinforcement in tension is the main source of predictable deformation capacity [9]. The rotation capacity corresponding to this failure mode can be calculated from a simplified component model in which only the reinforcement in tension, the slip of the shear connection and the beam flange in compression are assumed to be active [9, 10].

3.5 Limitation to low axial forces in the joint

The simplified assembly procedures given in Revised Annex J are limited to the calculation of joints mainly subjected to bending moments. More precisely, the axial force in the beam should not exceed 10% of the axial resistance of the latter. Beyond this limit, the distribution of internal forces, as well as the bending resistance of the joint, is assumed to be too much affected by the axial force. In [8], the possible unsafe character (till 20 to 25 %) of this limit has been demonstrated, and a reduction of the maximum axial force to 5% of the axial resistance of the beam seems more justified. An overview of the available procedures for distributions of internal forces in joints simultaneously subjected to bending moments and axial forces is given in [8].

4 REFERENCES

[1] EUROCODE 3, ENV - 1993-1-1, *Revised Annex J*, Design of Steel Structures, CEN, European Committee for Standardization, Document CEN / TC 250 / SC 3 - N 419 E, Brussels, June 1994.

[2] Steenhuis, M., Jaspart, J.P., Gomes, F. and Leino, T., "Application of the component method to steel joints", see [4].

[3] Tschemmernegg, F., Rubin, A. and Pavlov, A., "Application of the component method to composite joints", see [4].

[4] Wald, F., Gresnigt, A.M., Weynand, K. and Jaspart, J.P., "Application of the component method to column bases", Proceedings of the COST C1 Conference, Liège, September 17-19, 1998.

[5] SPRINT Contract RA351 on "Steel Moment Connections according to Eurocode 3. Simple Design Rules for Rigid and Semi-Rigid Joints", 1992-1996, Crif Liège (B), University of Liège (B), ENSAIS Strasbourg (F), CTICM (F), University of Trento (F), Labein Bilbao (SP).

[6] Tschemmernegg, F., "Deformation of semi-rigid composite joints", COST-C1 Proceedings of the Second State of the Art Workshop, Wald, F.(ed), European Commission Directorate-General XII, Brussels, 1994, 195 - 207.

[7] Huber, G., "Report of COST C1 short-term scientific mission to Liege", Institute of Steel and Timber Construction, University of Innsbruck, 1997, 24 pages.

[8] Jaspart, J.P., "Recent advances in the field of steel joints. Column bases and further configurations for beam-to-column joints and beam splices", Department MSM, University of Liège, 1997.

[9] Najafi, A.A. and Anderson, D., "Ductile steel-concrete composite joints", Composite Construction-Conventional and Innovative, Conference Report, IABSE, 1997, pp. 427-432.

[10] Anderson, D (ed), COST-C1 Composite steel-concrete joints in braced frames for buildings, European Commission, Luxembourg, 1997.

[11] Eurocode 3 ENV – 1993-1-1, "Design of Steel Structures", Commission of the European Communities, European Prenorm, Brussels, April 1992.